

Strategic Traffic Flow Management Concept of Operations

Goli Davidson^{*}, Jimmy Krozel, Ph.D.[†]
Metron Aviation, Inc., Herndon, VA, 20170

Steven M. Green[‡]
NASA Ames Research Center, Moffett Field, CA, 94035

Cynthia K. Mueller[§]
National Center for Atmospheric Research, Boulder, CO, 80307

With increases in weather-related delays, the Air Traffic Management (ATM) community is calling for enhanced functionality for integrating strategic weather information with Traffic Flow Management (TFM) decisions. This TFM Concept of Operations describes the language, process, and technologies required to increase the effectiveness of uncertain weather information when making strategic TFM decisions constrained by convective weather. TFM needs a mechanism to reason about probabilistic weather forecasts in a way that balances the safety and efficiency of traffic flows and ensures that uncertainty is logically taken into account. Building on the Collaborative Decision Making (CDM) paradigm, we enable the Collaborative Convective Forecast Product (CCFP) to capture multiple potential weather scenarios and provide a mechanism for air traffic managers and airline dispatchers to use probabilistic forecasts in their severe weather avoidance planning. A Probabilistic Decision Tree models the problem state space and maps to current weather avoidance practices, TFM decision points, and uncertain weather forecasts. Our concept also calls for new forecast products that include estimation of the uncertainty in weather predictions in a format that is relevant to the ATM decision making process. Finally, we need a decision support tool with algorithms to help make decisions using probabilistic forecast products.

Acronyms and Abbreviations

AOC	=	Airline Operations Center	NWS	=	National Weather Service
ATC	=	Air Traffic Control	SWAP	=	Severe Weather Avoidance Program
ARTCC	=	Air Route Traffic Control Center	TFM	=	Traffic Flow Management
ATCSCC	=	Air Traffic Control System Command Center	VIL	=	Vertically Integrated Liquid
ATM	=	Air Traffic Management			
AWC	=	Aviation Weather Center			
CCFP	=	Collaborative Convective Forecast Product			
CDM	=	Collaborative Decision Making			
CIWS	=	Corridor Integrated Weather System			
CWSU	=	Center Weather Service Units			
FCA	=	Flow Constrained Area			
GDP	=	Ground Delay Program			
GS	=	Ground Stop			
ITWS	=	Integrated Terminal Weather System			
MIT	=	Miles in Trail			
NAS	=	National Airspace System			

^{*} Senior Analyst, Research and Development Division, 131 Elden St., Suite 200

[†] Chief Scientist, Research and Development Division, 131 Elden St., Suite 200, AIAA Associate Fellow

[‡] Manager, En route Systems and Operations, M/S 210-10, AIAA Associate Fellow

[§] Project Scientist II, MMM/NCAR, P.O. Box 3000

I. Introduction

WITH increases in weather-related delays, the Air Traffic Management (ATM) community is calling for enhanced functionality for integrating strategic weather information with Traffic Flow Management (TFM) decisions. With a perfect picture of the future, traffic flow could be managed to a well known plan that optimizes the use of airspace and airport resources. Setting aside the significant strides achieved in weather prediction accuracy, current capabilities are far from accurate and precise enough to support a single-scenario approach to strategic TFM decisions. In this paper, we present an approach which introduces probabilistic weather forecasting and reasoning about multiple scenarios in order to develop a strategic TFM plan.

A. Single Scenario Forecasts

Currently, TFM decisions to avoid weather are made through the Severe Weather Avoidance Program (SWAP), initiated at the Air Traffic Control System Command Center (ATCSCC) and developed in coordination with National Air Traffic Control (ATC) facilities and Airline Operation Centers (AOCs). The primary weather source for prediction of weather constraints in the National Airspace System (NAS) is the Collaborative Convective Forecast Product (CCFP). This forecast product, shown in Figure 1, consists of an initial forecast produced by the Aviation Weather Center (AWC) in Kansas City merged with collaborative input by participating airline meteorologists and Air Route Traffic Control Center (ARTCC) Weather Service Units (CWSU). The result is a single-scenario product that forecasts convective weather in the NAS at two, four and six hours into the future. The CCFP serves as a common basis on which to base traffic flow decisions whereas in the past, traffic managers and airline dispatchers relied on separate forecast products.

The CCFP forecasts the convection coverage area, degree of coverage and confidence of the forecast based on participant input. The CCFP does a good job of indicating general areas where convective weather may develop but because of the chaotic nature of convection, it is difficult to obtain information four to six hours ahead of the event that can be used for ATM decision making. Further, it is unclear whether the CCFP provides enough accuracy and resolution to be useful for strategic planning.

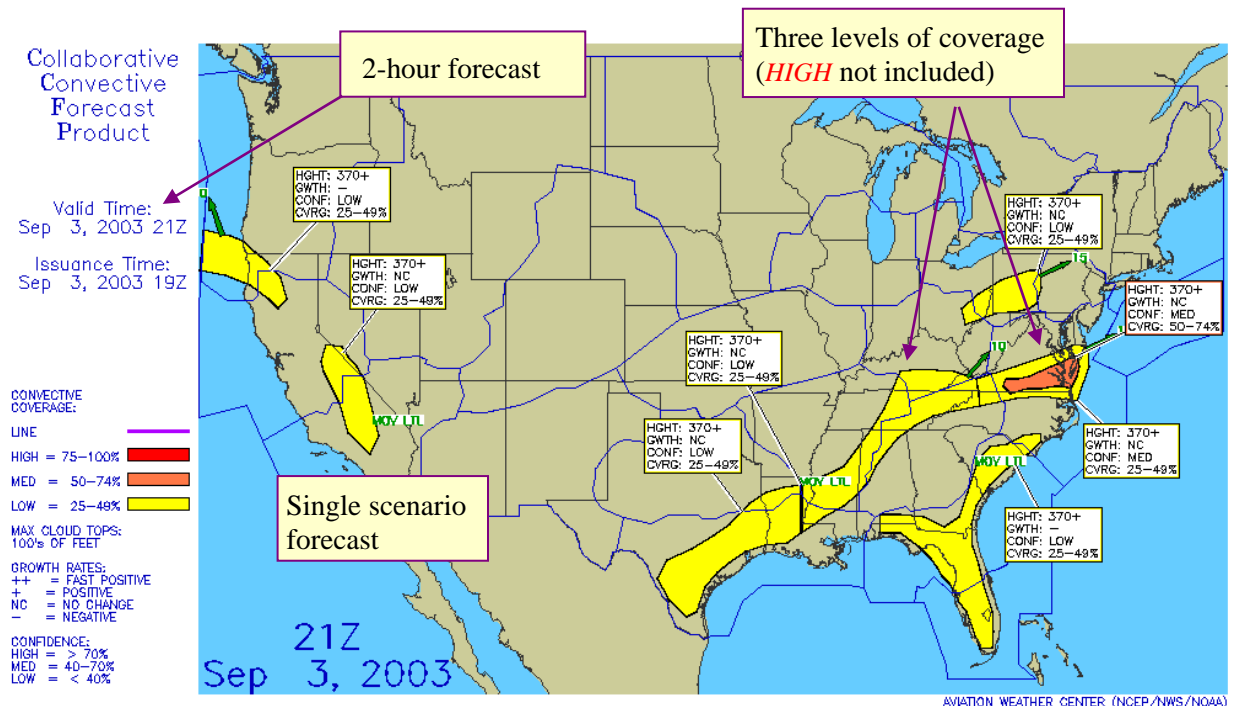


Figure 1. The CCFP provides a single view into the future with coarse probability of coverage.

B. Weather-Constrained Traffic Flow Management

Traffic managers and airlines start with a wide range of options to mitigate the effects of weather-related constraints. As the availability of jet routes, fixes or arrival slots decreases in the presence of turbulent or severe weather, the demand on the remaining resources increases, and some aircraft must be delayed to maintain safe separation standards. Options for absorbing this delay range from re-routes to departure delays, depending on how

far in advance the constraint can be predicted. Figure 2 illustrates these options against a timeline that starts when flights are upstream of the weather-related constraint (more than two hours from the event) to when flights are approaching or transiting the problem airspace (less than one hour to the event). Strategic options for mitigating weather-related delay include Ground Delay Program (GDP), Ground Stop (GS), Cancellation, and Miles-in-Trail (MIT) restrictions. If the decision cannot be made strategically, the tactical options are fewer: Vectoring or Holding. As shown in Figure 2, the cumulative delay of the affected aircraft increases sharply as delay-mitigation options are reduced. It is, therefore, most efficient to manage flights around the weather-related constraint strategically. This decision, however, is complicated by the uncertain nature of weather prediction. Strategic weather predictions are significantly less certain than tactical predictions, also indicated in Figure 2.

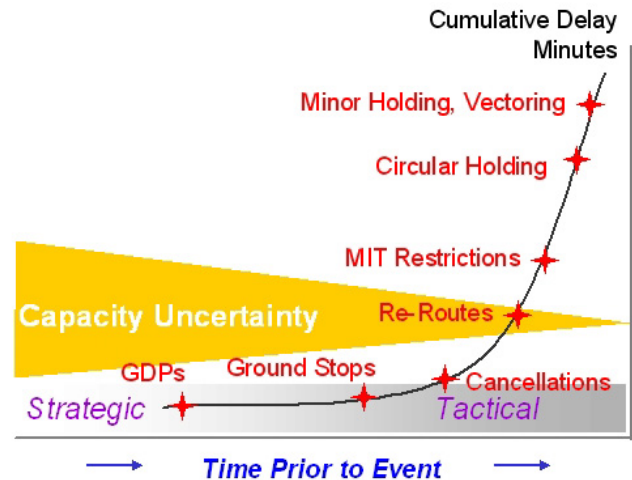


Figure 2. As time to the weather constraint decreases, options for mitigating the growing cumulative delay are limited.

C. Uncertainty in Weather Predictions

TFM decision makers continue to use informal processes to best predict the weather constraint scenarios they need to plan routes and form contingency plans. They must carefully assess the CCFP with the jet route structure to determine the need for re-routes to other jet routes or to playbook plays (predetermined reroute strategy). Two factors in making the right decisions are the accuracy and precision of the weather forecast. Traffic managers and airlines sometimes use other weather products, such as radar observations, forecasts and echo tops information from the Integrated Terminal Weather System (ITWS) or the Corridor Integrated Weather System (CIWS), to augment the CCFP with higher fidelity and more frequently available data. They need these complementary products to refine their knowledge of the probability of convection or other weather constraints. The additional details are necessary for contingency planning around these constraints without being so conservative as to leave valuable capacity unused. Not all NAS users are equipped with these additional products, and these other products still do not provide a probabilistic view of the strategic weather forecast.

Figure 3 shows an example where the CCFP forecast for June 27, 2002 did not provide sufficient detail to determine the tactical implications of strategic plans to route eastbound aircraft to the north of the weather. Flights between JFK and BOS were affected with a rush of arrival traffic that grid-locked BOS.

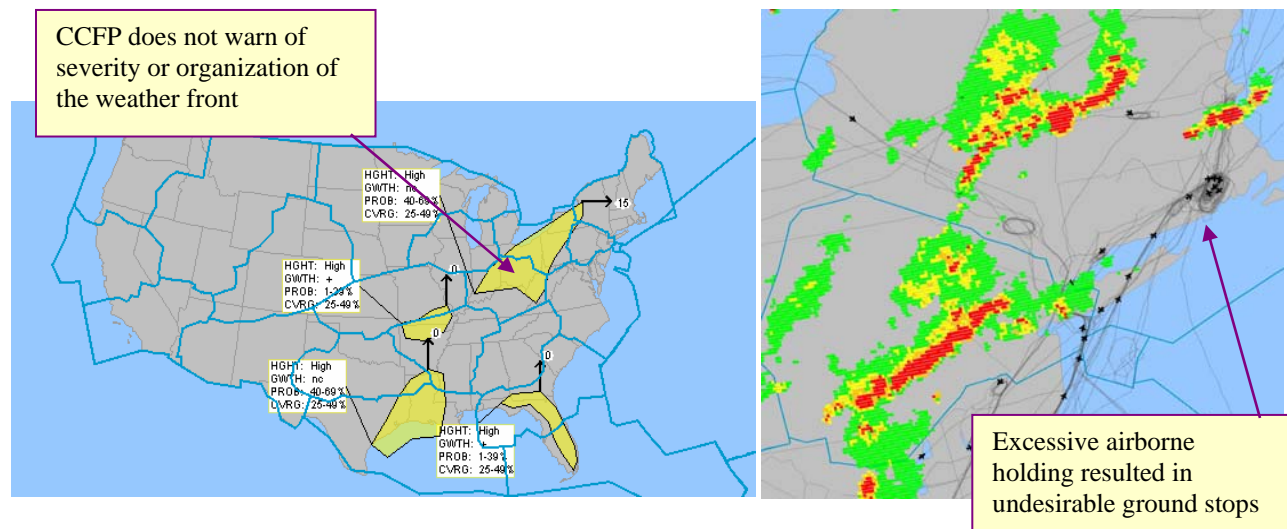


Figure 3. CCFP forecast for June 27, 2002 and the weather that ultimately materialized.

Weather predictions two to six hours before a given weather constraint (when aircraft have not yet departed) are not precise enough to base refined GDP initiatives on them. So, TFM decisions must be made with inaccurate or imprecise weather information. If weather does not materialize or is less severe than expected, the TFM-assigned ground delay served is unrecoverable. If unexpected convection occurs and the aircraft scheduled to cross this region are already in the air, drastic measures (such as a GS) must be used to stop the departure of new traffic until those aircraft in the air have been safely managed through the severe weather area.

There are many limitations to forecast accuracy, particularly beyond two hour horizons, and significant levels of uncertainty in weather forecasts will be a fact of life for the foreseeable future³.

II. Approach

The challenge in making TFM decisions under weather conditions is the presence of many types and dimensions of uncertainty in weather predictions. Weather predictions are more certain (and accurate) within an hour of an event and progressively less certain (and accurate) in further advance of the event. Furthermore, predictions can be uncertain with respect to the time and the location of the potential weather event. Additional uncertainty is associated with the rate of growth or decay, the severity and the organization of the potential event. The uncertainty that surrounds weather predictions is further complicated by our current inability to accurately represent the uncertainty of the forecast. Probability forecasts provide a mechanism to quantify the forecast uncertainty.

When dealing with TFM decisions, we first simplify weather events to mean convective weather that may incite pilots to request route changes or deviations of some kind to avoid the event. The (potential) event may be very small (i.e. a few cells) or very large (i.e. a weather front) and consist of convective activity, National Weather Service (NWS) precipitation of Level n (n ranges from 0 through 6), Vertically Integrated Liquid (VIL), echo top of altitude h , etc. We define,

Convective Weather Constraint: Pre-specified weather activity used to trigger an ATM decision

As already described, the current method of displaying weather predictions is with the single-scenario CCFP image for 2, 4, and 6 hour forecasts. We are concerned with providing information to ATM decision makers about the uncertainty associated with weather predictions that is directly relevant to the nature of their flow decisions. In addition to the likelihood that some particular weather phenomena will develop, it is equally critical to understand how likely it is to impact a specific traffic flow or region of airspace. Such data should provide decision makers with the ability to plan aircraft routes and traffic flows with consideration for the probability of potential weather events. We define,

Probabilistic Forecast: The expected convectivity at T minutes into the future, where each pixel on the map identifies the probability that the pixel contains convective weather.

Figure 4 shows a probabilistic forecast of a potential convective organization and probability of occurrence at each pixel. Green regions indicate 20% chance of squall-line associated with large-scale forcing with no gaps; dark gray indicate 25% chance of linear storms with gaps; light gray indicate 50% chance of afternoon convection with little synoptic forcing.

TFM Planning must incorporate uncertain weather information with the TFM decision making process to create a systematic approach for formulating control strategies that are robust to uncertainties in weather forecasts.

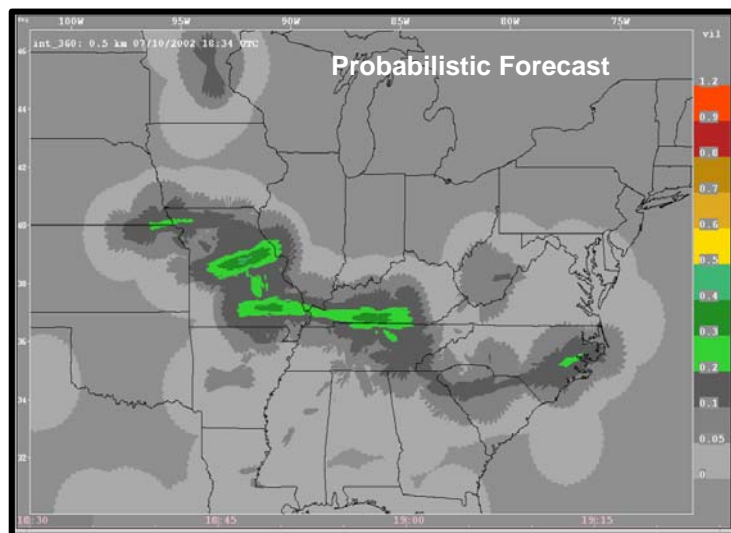


Figure 4. The Probabilistic Forecast shows organization of probable convection (Image courtesy of NCAR).

A. Probabilistic Decision Trees

The complex interaction between potential weather outcomes and TFM initiatives can be modeled using the discrete events of a Probabilistic Decision Tree. We start by modeling the potential weather outcomes. In Figure 5, each element (box) of the tree represents a potential weather scenario and a probability is associated with each. Scenarios either implicitly or explicitly represent uncertain weather information. We define,

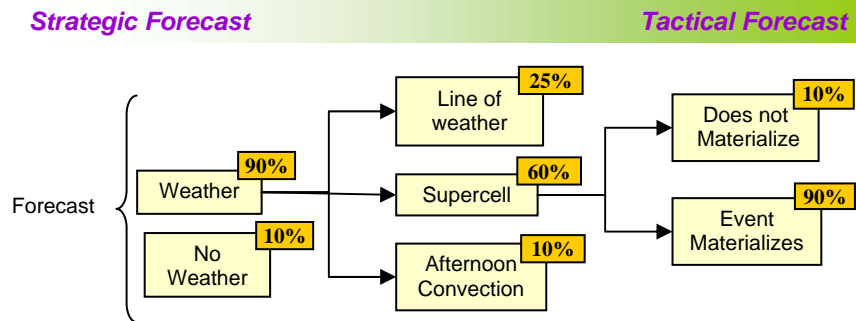


Figure 5: Model of potential weather outcomes.

Scenario: A single, general image representation of a potential expected traffic or weather outcome

Scenario Probability: A probability assigned to a scenario which provides relative probabilities between different future scenarios. In order to map to a branch of the decision tree, the sum of the probabilities for a set of scenarios may equal but not exceed 100%

Traffic Flow Managers currently use snapshots of weather forecasts and prefer discrete possibilities rather than the probabilistic forecasts, as shown in Figure 4. We identify the need for discretization of the probabilistic forecast into potential weather forecast scenarios. In Figure 6, we show the use of multiple deterministic forecasts to represent potential future weather organization outcomes, or *scenarios* as defined above. The scenario possibilities are that “no weather”, “moderate weather”, or “severe weather” will materialize. Probabilities are associated with each potential outcome. We define,

Weather Forecast Scenario: A discrete forecast with independent basis; a set of weather forecast scenarios expresses all significantly probable convective outcomes.

These potential weather scenarios establish the frame of the probabilistic decision tree. Assuming a 2-hour forecast and decision cycle and initial discretization of potential outcomes 6-hours before the weather constraint, forecast scenarios are updated next at the 4-hour forecast point. These updates allow us to refine the model of potential weather outcomes with more accurate weather predictions. Figure 7 shows how updates in weather prediction information help to refine and adjust the view of the future.

Later we discuss the relationship between TFM decision making and these scenarios.

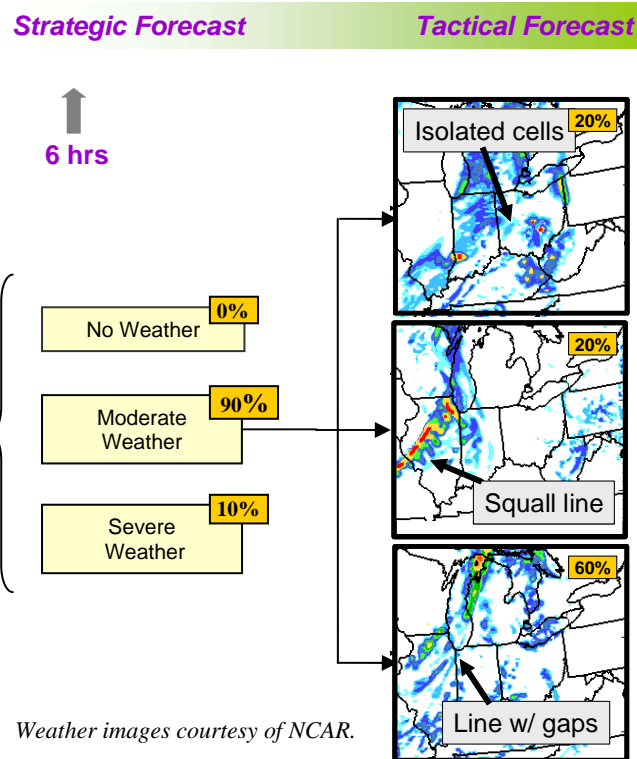


Figure 6. Strategic view of organization of probable convection and the associated scenario probability.

decisions related to one decision point in time for one “problem.” At later points in time, the tree is rebuilt for the evolution of that problem as it unfolds. The probabilistic decision tree is a dynamic tool for assessing the needed information for the decision at hand.

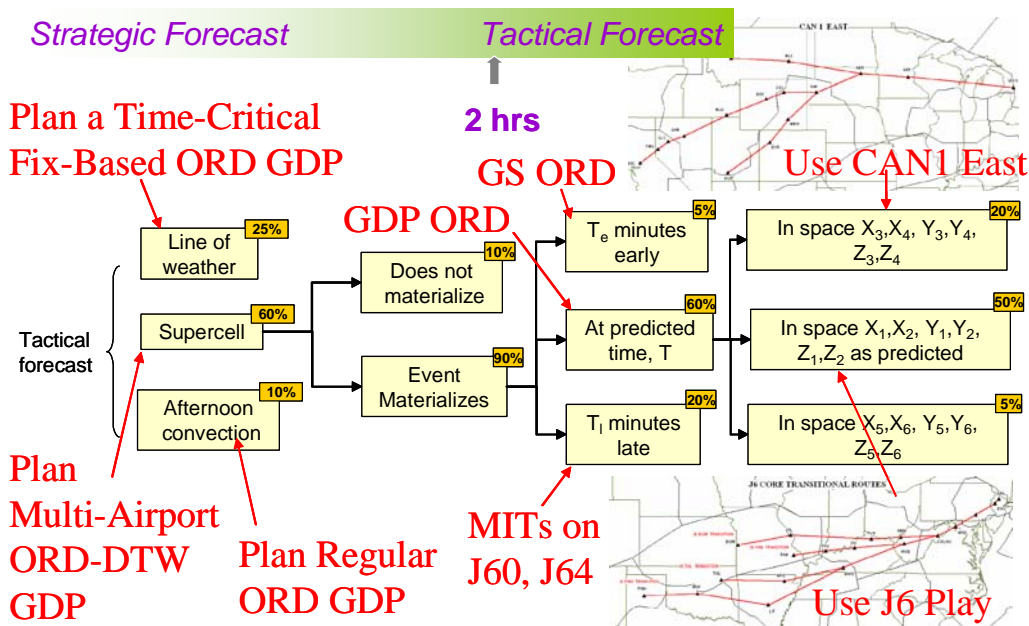


Figure 9. An ATM-Weather Probabilistic Decision Tree illustrates the TFM mechanism needed.

Real-world data will show the relationship between nodal decision points and the Probabilistic Decision Tree with discrete points along the time horizon. When using both the national route system and playbook plays, there are clear decision points, as shown by the nodes in Figure 10. At any point where there is more than one path to the destination airport; decision makers must consider the safety, congestion impact, and efficiency of the route.

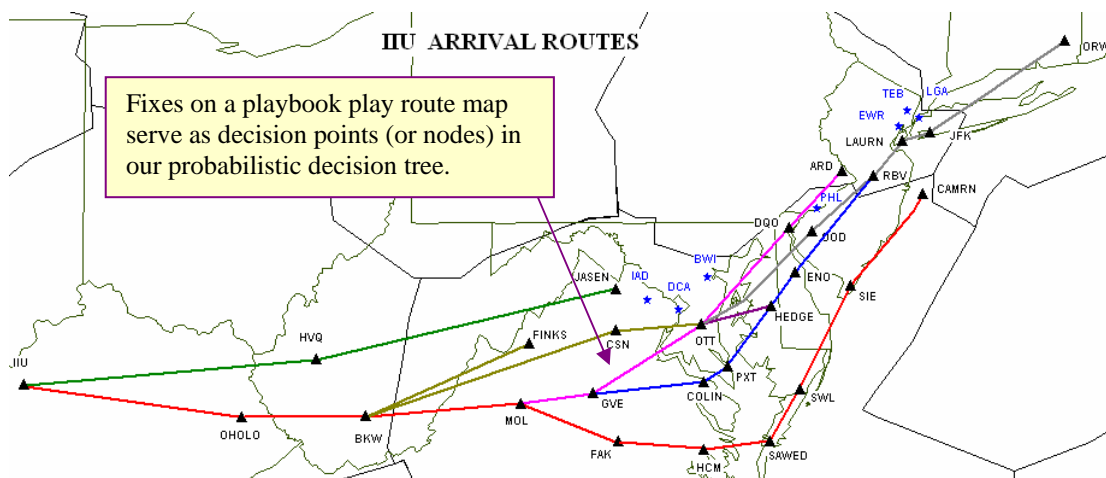


Figure 10. Playbook plays provide many options for routing around weather, but traffic managers and airlines must decide which to use.

The probabilistic decision tree adds the layer of potential TFM decisions to processes which themselves may have alternate choices. A DST could be used to compare the choices of TFM actions against all the probable weather outcomes and determine which choice of TFM actions (what sort of plan) would have the best outcome.

B. Robust Algorithms with Stochastic Basis

For ATM decision makers to use uncertain weather information in determining control strategies, we must define the relationships between the Probabilistic Decision Tree, weather avoidance practices, temporal and spatial TFM decision points, and uncertain weather forecasts. This paper proposes this concept which calls for such a product to be developed if possible. Algorithms are used to formalize these relationships and must address strategic and tactical decisions as well as varying degrees of uncertainty in the input data. The problem approach consists of identifying the nature of uncertainty, devising a solution strategy and finally identifying potentials solution. We have already proposed how probabilistic weather forecasts could identify a range of potential futures. We simplify this problem by reducing the solution space to discrete alternate futures. We have a choice of several strategies for determining the most likely solution. This process is described in Figure 11 where solution characteristics are also described.

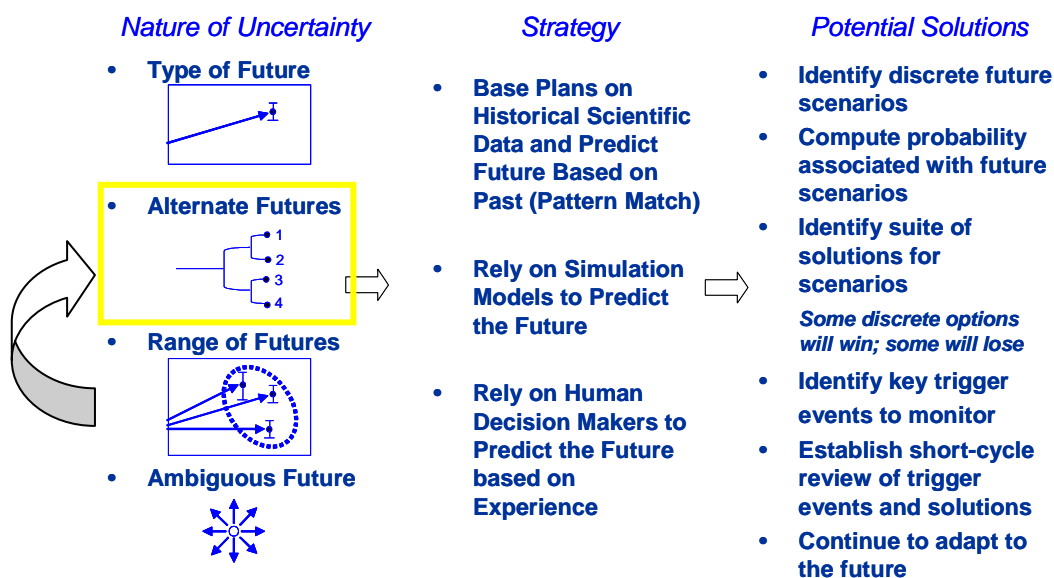


Figure 11. The problem approach consists of identifying the nature of uncertainty, devising a solution strategy and finally identifying potentials solution. We simplify the range of futures to a discrete set.

Weather scenario probabilities can be used to establish re-route options as a traffic specialist at the ATCSCC or AOC would. This exercise relies on input from subject matter experts combined with future weather displays. We hypothesize a graphical interface to capture the human interaction with the system.

This risk mitigation and optimization is currently performed informally with varying degrees of success. Our probabilistic decision tree approach is intended to demonstrate the effect of time on the options available to traffic flow managers. As we approach an event time of interest, weather forecasts become more accurate. At the same time traffic flow managers must implement increasingly tactical maneuvers to grant pilot requests to avoid weather as options such as ground delays and ground stops cannot be used for aircraft already airborne. Uncertainty management takes place to best estimate the time and space in which the convection constraint/event will impact the traffic flows. Control strategies are designed based on continually adjusted forecasts. Figure 9 illustrates the use of the probabilistic decision tree as time approaches the potential weather event.

Further research is needed to develop the algorithms to relate the scenario probabilities and weather avoidance decisions. These algorithms must be flow-based rather than aircraft-based. This allows us to address air traffic controller concerns of airspace inefficiency and high workload related to individually managing aircraft. Although the restriction of aircraft to flows appears to limit airline preferences, it actually promotes airline flexibility in route planning. Dispatchers may request pre-determined re-routes around weather constraints by name (via the National Playbook or other jet routes) with greater chance of approval. In the future, expansion of the route and Playbook system will further increase airline flexibility.

C. New Forecast Products

Given the proposed framework for strategic TFM in the presence of weather uncertainties, we identify the need for a weather product that is suited to this application. Such a product should include an estimation of the uncertainty in convective weather constraints in a format that is relevant to the ATM decision making process so that decision makers can logically and quantifiably determine robust TFM strategies. We look to the weather forecasting community to develop the ability to segregate discrete weather scenarios, each with its own occurrence, instead of an aggregate or averaged representation of multiple forecasts into one. By organizing predictions in the form of discrete weather scenarios we can combine a TFM-relevant forecast with a “weather-relevant” method of TFM decision making to create a single interdisciplinary product.

We must identify a reasonably effective strategy that will serve the airspace users well in the event that the most likely scenario does not unfold. Decision should not be based on the most likely outcome, or the long-shot, but should be balanced to achieve moderate success with minimal risk. To make strategic TFM decisions that can respond to change and uncertainty as traffic approach potential problem areas, we need forecast product to help clarify and depict the various weather scenarios and their likelihood.

D. Feasibility of Stochastic Approach

The Probabilistic Decision Tree and multi-scenario CCFP concept can be used to measure cumulative delay between the strategic TFM planning approach and the wait-and-see approach. Using a Flow Constrained Area (FCA) or similar function, we can model the weather constraint and show the result of a range of TFM initiatives beginning strategically in advance of the constraint and continuing up until the constraint. We expect an increase in cumulative delay as initiatives are imposed later and later as shorter time horizons typically require greater deviation to avoid the same constraint. This result is nothing new to the community; rather the exercise will highlight the system integration issues required to successfully integrate decision trees with probabilistic weather scenarios. It also allows us to establish the correct metrics for the concept.

Ultimately, a proof of concept is needed to demonstrate the feasibility of the Probabilistic Decision Tree approach, integrating the probabilistic forecast and algorithms to revealing the details that complicate most concept implementations. A proof of concept environment also serves as a test bed for algorithms designs.

III. Conclusion

Due to the challenge in gaining significant improvements in two- to six-hour forecasts, the current single-scenario approach to predicting the effects of weather on air traffic has reached a limit. Significant levels of uncertainty will be present in weather forecasts for the foreseeable future. Between “certainty” and limit beyond which the uncertainty is so great for a piece of data that the data is essentially useless, we need a probabilistic approach to TFM decisions making. In this concept, we have described such an approach to modeling and using uncertainty associated with weather predictions in TFM. Probabilistic decision trees are used first to characterize potential weather outcomes, and then to identify candidate TFM actions. The final picture is a set of decision trees that combines both types of information. This requires defining the relationships between the probabilistic decision trees, ATM weather avoidance practices, TFM decision points, and uncertain weather forecasts. With this information, decision makers have the ability to affect flows or portions of flows rather than try to manage flights individually. We also identify the need for forecast products that include estimation of the uncertainty in convective weather constraints in a format that is relevant to the ATM decision making process. Finally, we need a decision support tool with algorithms to help make such decisions using probabilistic forecast products.

IV. References

- ¹ Ball, M. O., Hoffman, R. L., and Vossen, T., “An Analysis of Resource Rationing Methods for Collaborative Decision Making”, *Proc. ATM 2002*, Capri, Italy, 2002.
- ² Brennan, M., Thompson, T. R., Bradford, S., Liang, D., “Using Historical Flight Data to Evaluate Airborne Demand, Delay, and Traffic Flow Control”, *Proc. ATM 2003*, Budapest, Hungary, 2003.
- ³ Committee for a Workshop on Weather Forecasting Accuracy for FAA Air Traffic Control, “Weather Forecasting Accuracy for FAA Traffic Flow Management: A Workshop Report,” National Academies Press, Washington, D.C., 2003.
- ⁴ Courtney, Kirkland, Viguerie, “Managing Uncertainty,” *Harvard Business Review*, Presidents and Fellows of Harvard College, 1999.
- ⁵ DeLaura, R., and Allan, S., “Route Selection Decision Support in Convective Weather: A Case Study of the Effects of Weather and Operational Assumptions on Departure Throughput”, *Proc. ATM2003*, Budapest, Hungary,

2003.

- ⁶ Evans, J. E., Robinson, M., Crowe, B., Klinge-Watson, D., and Allan, S., "Reducing Severe Weather Delays in Congested Airspace with Weather Decision Support for Tactical Air Traffic Management", *Proc. ATM2003*, Budapest, Hungary, 2003.
- ⁷ Hoffman, B., Krozel, J., and Jakobovits, R., "Potential Benefits of Fix-Based Ground Delay Programs to Address Weather Constraints," *AIAA Guidance, Navigation, and Control Conf.*, Providence, RI, August, 2004.
- ⁸ Nilim, A., El Ghaoui, L., and Duong, V., "Multi-Aircraft Routing and Traffic Flow Management under Uncertainty", *Proc. ATM 2003*, Budapest, Hungary, 2003.
- ⁹ Pepper, J. W., Mills, K. R., and Wojcik, L. A., "Predictability and Uncertainty in Air Traffic Flow Management", *Proc. ATM 2003*, Budapest, Hungary, 2003.
- ¹⁰ Wilson, J.W., Crook, N. A., Mueller, C. K., Sun, J. and Dixon, M., "Nowcasting Thunderstorms: A Status Report," *Bulletin of the American Meteorological Society*, No. 79, Boston, MA, 02108, 1998, pp., 2079-2099.